ORNL/TM--10629

DE88 008016

Engineering Physics and Mathematics Division

EXECUTIVE SUMMARY

THE OAK RIDGE NATIONAL LABORATORY STRATEGIC DEFENSE INITIATIVE SHIELD OPTIMIZATION PROGRAM

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19980513 139

DATE PUBLISHED — April 1988

Prepared by
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
operated by
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under Contract No. DE-AC05-84OR21400

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Accession Number: 1972

Publication Date: Apr 01, 1988

Title: Oak Ridge National Laboratory Strategic Defense Initiative Shield Optimization Program

Personal Author: Santoro, R.T.; Gabriel, T.A.

Corporate Author Or Publisher: Oak Ridge National Laboratory, Oak Ridge, TN 37831 Report Number: ORNL/TM-10629

Descriptors, Keywords: Van Allen Belt Proton Radiation Nuclear Weapon Energy Neutron Carbon Electron KEW Millimeter Degradation Satellite Survivability Damage Shield NPB DEW Space Ionization Model Material

Pages: 021

Cataloged Date: Oct 17, 1989

Contract Number: DE-AC05-84OR21400

Document Type: HC

Number of Copies In Library: 000001

Original Source Number: DE88-008016

Record ID: 20872

Source of Document: NTIS

NOT IN DROLS 4/28/98

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ABSTRACT

Scoping studies have been completed to estimate radiation-induced damage in silicon-based electronic components carried on a satellite. The analyses were completed for natural (Van Allen belt protons and electrons, solar flares, and galactic cosmic rays) and man-made (nuclear and directed neutral particle beam weapons) radiation expected to be encountered by an SDI satellite or weapon platform. The Van Allen belt protons, depending on altitude and orbital inclination, were found to be the most stressing natural radiation threat. Nuclear weapon radiation, depending upon the weapon yield and distance of the detonation from the satellite, and neutral particle beam radiation were found to terminally destroy electronic components. Calculations were also made to estimate the amount of local shielding required to extend mission performance. These shields were optimized for minimum weight for specified damage thresholds. All of the calculations were carried out assuming the presence of a thin primary shield tailored specifically for survivability against an incident low mass kinetic energy weapon projectile and which affords minimal protection against energetic radiation.

1. EXECUTIVE SUMMARY

The Oak Ridge National Laboratory (ORNL) Shield Optimization Program is funded by the Air Force Weapons Laboratory (AFWL) as part of the Defensive Shield Demonstration Program (DSDP) for the Strategic Defense Initiative (SDI) Survivability, Lethality, and Key Technologies (SLKT) Directorate. The purpose of this research program is:

1. To perform scoping studies to assess the impact of radiation on SDI space deployed systems. This includes both the natural radiations of space and the man-made radiations from space-detonated nuclear weapons or directed energy neutral particle beams. The natural radiation modes include the Van Allen belt protons and electrons, solar flare protons and alpha particles, and galactic cosmic radiation.
2. To determine the radiation protection afforded to electronic equipment by a low mass kinetic energy/laser weapon shield and the composition and configuration of secondary shielding that must be placed around silicon based electronic circuits to reduce the dose rate to levels that assure long term operation and mission completion.
3. To optimize these secondary shields, that is, determine the minimum shield weight and material order/configuration for a specified damage reduction and shield composition.

The damage levels to silicon based circuits and electronic components are characterized by response parameters that depend on the radiation modes incident on the shields and/or the circuit type being protected. These damage responses include:

1. the total energy deposition,
2. ionization energy deposition,
3. displacement energy deposition,
4. particle fluxes and fluences, and
5. equivalent 1-MeV neutron fluence.

The purpose of the calculational effort summarized here and reported in detail in Reference 1 was to determine the range of these responses for the various radiation modes and to obtain initial damage criteria for silicon circuit components.

1.1. DETAILS OF THE CALCULATIONS

At the time this scoping study was initiated, no SDI weapon platforms with accompanying sensor/electronic components were available. Therefore, all of the calculations reported in Reference 1 were carried out using an idealized representation of an SDI satellite system. This geometry is shown in Figure 1. The outer shield is a low mass, layered assembly that was designed primarily for protecting the satellite against kinetic energy and laser weapon threats. The inner radius of the idealized satellite is 1.0 m and the outer shield thickness is nominally 0.1 m. Electronic circuitry is simulated by a 20-mm-radius silicon sphere located at the center of the satellite. A spherical radiation shield that is optimized in weight and material as a function of damage surrounds the interior silicon sphere. The remainder of the interior of the satellite is treated as a void. No consideration was given to the presence of materials/equipment that simulate on-board weapon or weapon support systems. In an actual SDI system, this equipment would provide additional shielding for critical electronics located in the interior regions of the satellite.

The results of this scoping study were obtained using several well established radiation transport codes/systems. These included the CALOR code package[2], (HETC[3], MORSE[4], MICAP[5], and EGS[6]) and ANISN[7] coupled with the shield optimization code ASOP[8]. The CALOR code system (see Figure 2) allows for the transport of nucleons, pions, electrons, positrons, muons, and photons and was used to estimate the damage in the silicon sphere from the natural radiation modes. The HETC code treats nucleons, pions, and muons. The EGS code treats photon and X-rays. The MICAP system calculates specific radiation responses in detectors and was used in conjunction with MORSE to establish the damage parameters in the silicon due to low energy neutrons (energy <20 MeV).

All of the calculations were carried out using current state-of-the-art transport cross-section data taken from the DLC-31[9] and VITAMIN-E[10] cross-section libraries.

Radiation damage effects were calculated from both ionization and atomic displacements. That is,

$$D\ (\text{total}) = D\ (\text{ionization}) + D\ (\text{displacement}).$$

Ionization occurs due to radiation induced charging of the thin oxide regions (nonconducting regions) which generate space-charge fields at the silicon surface. These induced fields result in voltage offsets or shifts in the turn-on voltages of the electronic circuits that lead to circuit degradation and failure. This effect is also responsible for single event upsets and latch-up phenomena. These kinds of damage are generally short term and depend strongly on the rate at which the dose is delivered.

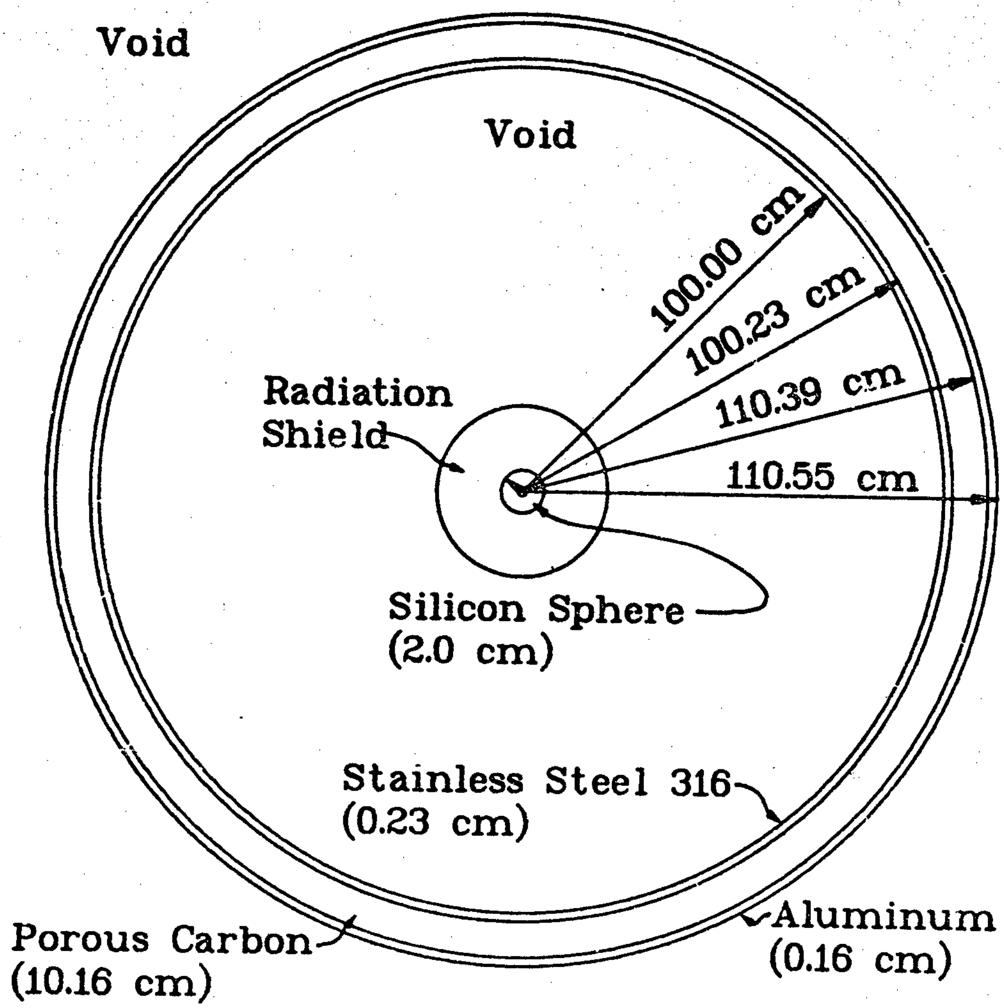

Figure 1. The spacecraft model used in the calculations (see Table 1 for the composition of components).

Table 1

Materials Used in the Transport Calculations

Material	Density(g/cm^3)	Weight%	Atomic Weight	Atom Density $(barn\text{-}cm)^{-1}$
Silicon	2.35	100% Si	28.09	5.039-2[a]
Aluminum	2.70	100% Al	26.98	6.028-2
Porous Carbon	0.10	100% C	12.00	5.019-3
Stainless Steel 316	7.95	17.0% Cr	52.00	1.566-2
		1.7% Mn	54.94	1.482-3
		2.5% Mo	95.94	1.248-3
		12.0% Ni	58.70	9.789-3
		1.0% Si	28.09	1.705-3
		65.8% Fe	55.85	5.641-2
Iron	7.86	100% Fe	55.85	8.476-2
Lead	11.35	100% Pb	207.2	3.299-2
Lithium Hydride	0.80	87.3% Li	6.94	6.060-2
		12.7% H	1.01	6.060-2
Borated Polyethylene	1.00	10.0% B	10.81	5.580-3
		12.4% H	1.01	7.505-2
		77.6% C	12.01	3.885-2

[a]Read as 5.039×10^{-2}.

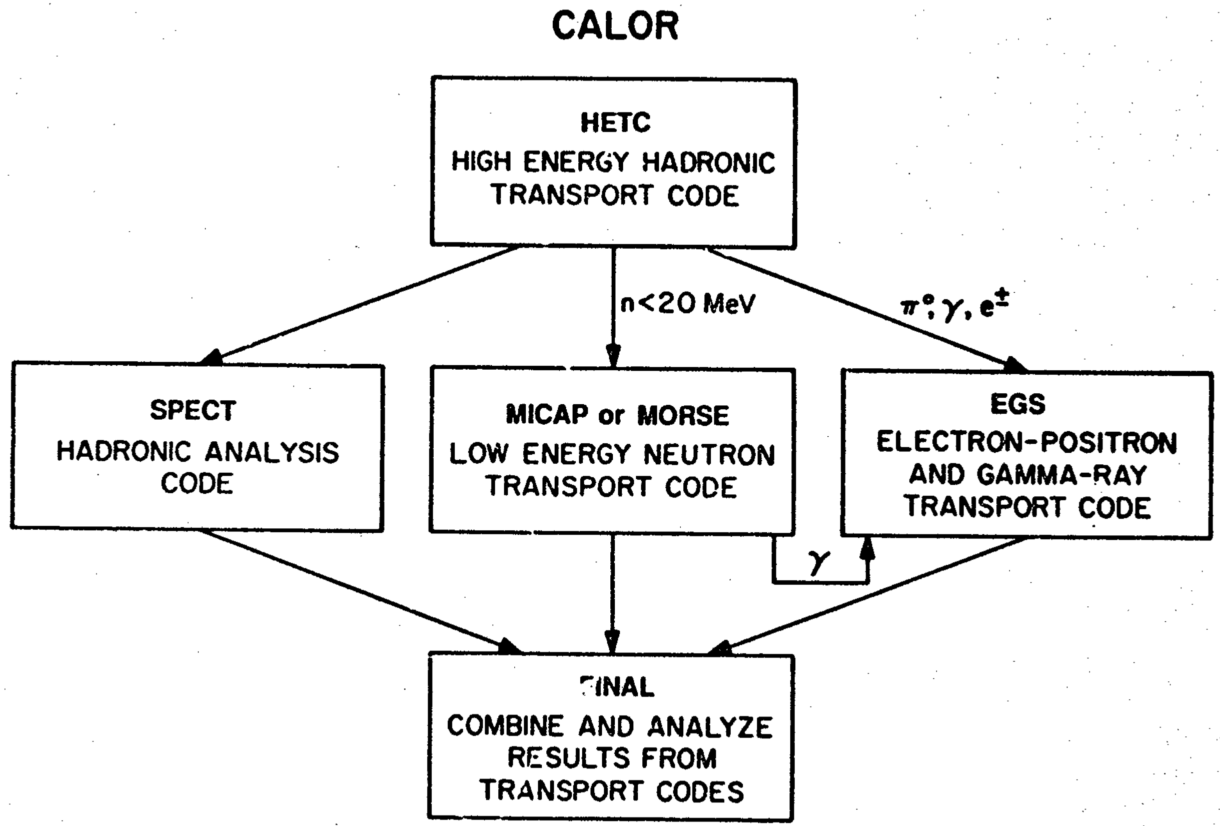

Figure 2. Flow diagram of the CALOR code system.

Any energetic particle can induce displacement damage. Neutrons and energetic charged particles (electrons, protons, alpha-particles, heavy ions) are the most important. Neutrons do not interact directly with the electrons in the circuit material, but lose energy only as the result of nuclear interactions. As a result, damage from neutron radiation is more important than for the charged particles which cause damage as the result of ionization energy loss. Neutrons produce primary knock-on atoms which in turn can produce additional displacements.

1.2. SUMMARY

The calculations and results described below represent the efforts of an initial scoping study to assess the effects and magnitude of natural and man-made radiation modes on the performance of electronic components in an SDI satellite/weapon system surrounded by a thin shield. The shield is designed principally to provide protection of satellite components against low mass, high-velocity kinetic energy weapon projectiles.

The natural radiation environment of space does not pose a significant threat to the performance of the KEW shield or to the electronic components borne by the satellite provided they are located within the shield and generally away from the surface of the system. Table 2 summarizes the yearly dose rates from natural radiation in the idealized electronic circuit/package, i.e., the 20-mm-radius silicon sphere (see Figure 1) from natural radiation. The galactic and solar flare protons will not have a serious impact on silicon based circuit performance even after a long duration (10 years) in space. The accumulated dose from these radiation modes will be far below the threshold of damage for typical circuit components such as those described in Figures 3a and 3b.

Van Allen belt proton radiation gives rise to a substantially greater annual dose rate and is strongly dependent on both the altitude and orbital inclination at which the satellite is deployed. The Van Allen belt proton dose rate varies widely, but, in general, no appreciable damage will be sustained by those circuits that are located well within a shielded satellite or isolated by other on-board equipment. Single event upsets and circuit latch-ups may occur, but the magnitude and regularity are not expected to be overwhelming.

The large dose rate from Van Allen belt electron radiation is entirely a surface phenomena. That is, all of the energy of the radiation is deposited in the first few millimeters of the shield. The impact on shielded sensitive electronics is negligible, but damage may occur in other critical components such as antennae, mirrors, or sensors mounted on the satellite surface or through the outer shield. These components would also be severely damaged by exposure to the Van Allen belt protons.

Space detonated nuclear weapons and directed energy neutral particle beams represent the greatest short term threat to the satellite and electronic equipment.

Table 2

Yearly Dose to the Silicon Due to
Natural Radiation Environments

Radiation Environment	Dose Rate (Rads/year)
Van Allen Belt Protons[a]	30 – 43,500
Galactic Protons[a]	0.5 – 1
Solar Flare Protons[a,b]	85 – 300
Van Allen Belt Electrons[c]	100 – 100,000

[a]KEW Shield and unattenuated primary protons only
[b]Assumes 5 flares per year
[c]Surface effect, dose in 0.035 cm of Si following 0.254 cm of Al shielding

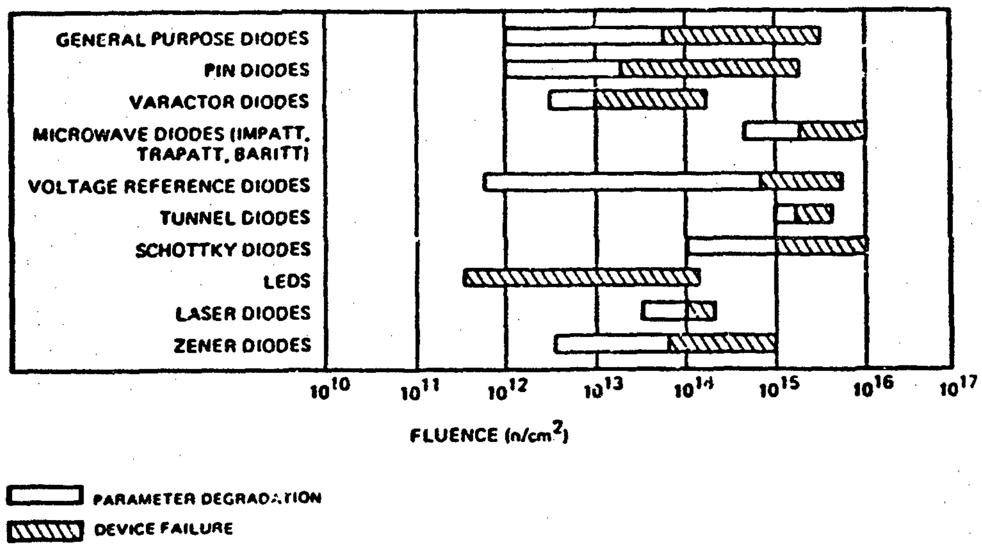

Figure 3a. Device degradation versus fluence for several diode types.

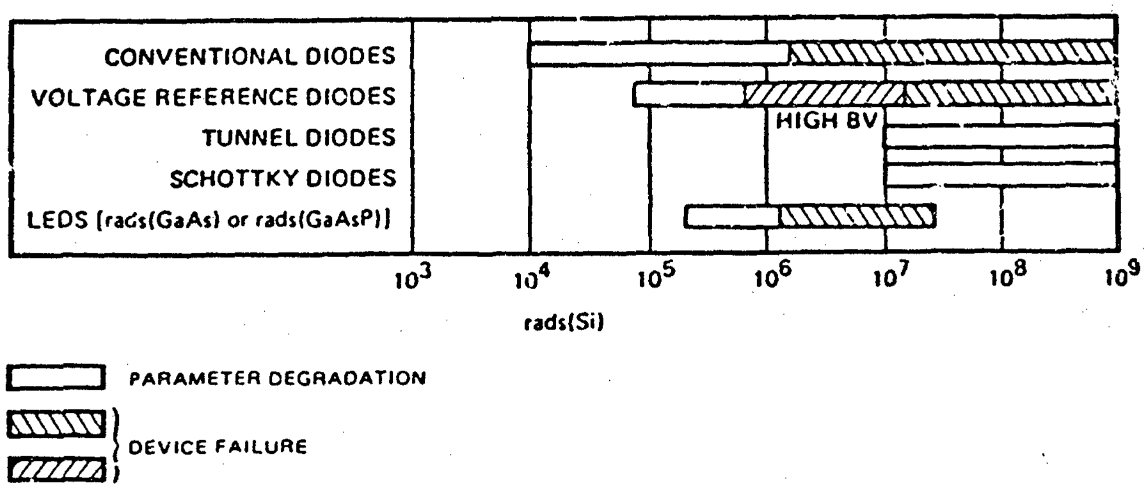

Figure 3b. Device degradation versus ionizing dose for several diode types.

The thin KEW shield does not have the capability to reduce the dose/dose rate from neutrons and gamma radiation from either a fission or fusion weapon to acceptable levels. Survivability of the satellite and electronics depends on the distance at which the detonation occurs and the yield of the weapon (see Figure 4 and Table 3). The preponderate radiation from a nuclear weapon, however, is in the form of X-rays, most of which is absorbed in the surface layers of the shield and result in an energetic hydrodynamic like impulse, and, depending on the black body temperature of the weapon and yield, may deliver large doses to on-board electronic equipment. Surface and immediate subsurface damage will generally predominate. The single event upset and latch-up rates in vital circuits due to weapon radiation may cause mission failure for satellites that are near the limit of the keep-out distances suggested in Figure 4.

To evaluate the threat of directed particle beams, preliminary calculations were performed for incident 50-, 100-, and 200-MeV neutral hydrogen particle beams*. Calculations were performed to estimate the energy deposition from unattenuated primary protons only and also to estimate the energy deposition from both primary and secondary particles. As indicated in Table 4 for the 50-MeV proton beam, no dose to the silicon occurs because the KEW shield surrounding the spacecraft is sufficiently thick to completely stop the incident beam. For the 100- and 200-MeV proton beams the results show that the addition of a semi-optimized Pb/BP shield totally mitigates the unattenuated primary ionization. For the 200-MeV proton beam the results further show an approximately 10^3 decrease in the silicon dose when both primary and secondary particles are transported. It should be noted that the primary protons have been completely stopped and do not contribute to the dose. This dose rate is capable of causing temporary damage or data flow interrupt if the spacecraft remained in a one amp proton beam for one second. Directed energy weapons will severely impact the performance and survivability of the spacecraft. However, it is not anticipated that weapons of this type will be of an immediate threat since this weapon is still in the early development stage.

An idealized satellite geometry was considered throughout this study. It does not account for the existence of additional shielding material between the shield and the sensitive electronic component. Studies were completed to determine the requirements for additional shielding surrounding the silicon sphere. One-dimensional radiation transport methods coupled to a shield optimization processor were used to establish the additional local minimum weight/damage reducing shielding requirements. These data obtained were used to establish local shielding material parameter space and to provide some insight into the effects of these materials on the survivability of the satellite. Some typical results are given in Tables 5 and 6.

The results reported here are for one event weapon detonations and single neutral particle beam illumination. No consideration was given to multiple hits

* (treated as proton beams in the analysis)

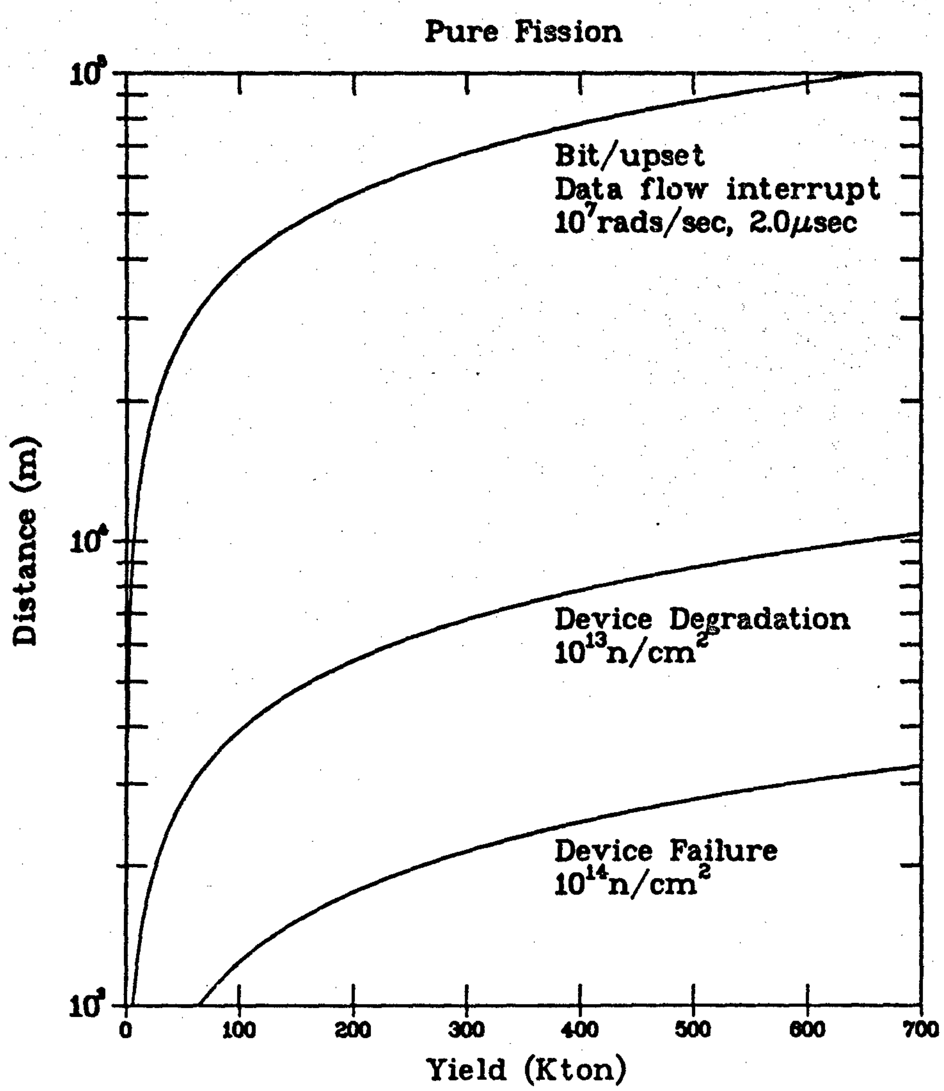

Figure 4. Device deterioration as a function of weapon yield, and distance for an idealized pure fission spectrum.

Table 3

Radiation Damage Parameters from Pure Fission, Prompt Gamma Rays, and Pure 14 MeV Radiation

	Responses ($R \cdot m^2$/kTon)		
R	Pure Fission	Prompt Gamma Rays	Pure 14 MeV
Flux > 0.11 MeV (cm^{-2})	1.54+18[a]		1.09+19
DPA in Si (dpa)	4.54−03		3.02−02
Damage Energy in Si (rads)	9.80+07		6.50+08
Neutron Energy Deposition in Si (rads)	2.34+08		1.56+10
Gamma-Ray Energy Deposition in Si (rads)	9.12+07	2.72+09	1.33+09

[a]Read as 1.54×10^{18}

Table 4

Dose Rates to the Silicon Due to Directed Particle Beam Weapons[a]

Particle Energy (MeV)	Shield Configuration	Dose Rate (Rads/sec/amp) Unattenuated P[b]	P + S
50	KEW	0.0	≈ 0.0
100	KEW	2.87×10^7	NC[c]
100	KEW + Pb/BP[d]	0.0	NC
200	KEW	1.23×10^7	1.64×10^7
200	KEW + Pb/BP[d]	0.0	2.42×10^4

[a]Assumes particle beam has diverged to spacecraft radius.
[b]P = primary, P + S = primary + secondary.
[c]Not Calculated.
[d]Pb/BP = 2.6 cm lead + 16.2 cm borated polyethylene.

Table 5

Optimized Radiation Shield Weights as a Function of Dose and Shield Composition for a Thermonuclear Source[a]

Dose (Rads(Si)·m²/kT)	Dose reduction	Shield Weight (kg) Pb/BP[b]	Pb/LiH
1.72×10^{10}	1	0.0	0.0
1.14×10^{10}	1/3	5.13	2.39
8.58×10^{9}	1/2	15.55	9.09
5.72×10^{9}	2/3	43.32	27.49
4.29×10^{9}	3/4	73.32	48.80

[a]90% 14 MeV neutrons and 10% fission source, neutrons and prompt gammas

[b]borated polyethylene

Table 6

Optimized Radiation Shield Weights as a Function of Dose and Shield Composition for a Fission Source

Dose (Rads(Si)$\cdot$m^2/kT)	Dose reduction	Shield Weight (kg) Pb/BP[a]	Pb/LiH
2.96×10^9	1	0.0	0.0
1.44×10^9	1/2	1.15	1.15
9.93×10^8	2/3	2.89	2.84
2.98×10^8	9/10	20.22	19.73

[a]borated polyethylene

wherein the structural integrity of the shield may be violated or the single event/latch-up rate is so prohibitive that total failure of the system occurs.

Finally, it should be noted that all of the results reported here were obtained using available response functions for dose, damage, single-event upset, etc. Some of the damage responses data must be re-evaluated and updated to reduce the uncertainties in the results that may be as large as a factor of two for the present data.

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